Volume 1: The LBNF and DUNE Projects

LBNF/DUNE Conceptual Design Report (DRAFT)

May 13, 2015

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Chapter 1

Introduction to LBNF and DUNE

The global neutrino physics community is developing a multi-decade physics program to measure unknown parameters of the Standard Model of particle physics and search for new phenomena. It is based on a leading-edge, dual-site experiment for neutrino science and proton decay studies, the Deep Underground Neutrino Experiment (DUNE), hosted at Fermilab in Batavia, IL. The facility required for this experiment, the Long-Baseline Neutrino Facility (LBNF), will be an internationally designed, coordinated and funded program, comprising the world's highest-intensity neutrino beam at Fermilab and the infrastructure necessary to support the massive DUNE cryogenic far detectors installed deep underground at the Sanford Underground Research Facility (SURF), 800 miles (1,300 km) downstream, in Lead, SD. LBNF will provide the facilities to house the DUNE near detectors on the Fermilab site. LBNF and DUNE will be tightly coordinated as DUNE collaborators design the detectors and infrastructure that will carry out this experimental program.

The LBNF scope includes:

- an intense neutrino beam aimed at a far site
- conventional facilities at both the near and far sites
- cryogenics infrastructure at the far site to support the DUNE liquid argon time-projection chamber (LArTPC) detector

The DUNE scope includes:

- a high-performance neutrino detector and beamline monitoring system located a few hundred meters downstream of the neutrino source
- a massive LArTPC neutrino detector located deep underground at the far site

With the facilities provided by LBNF and the detectors provided by DUNE, the DUNE Collaboration proposes to mount a focused attack on the puzzle of neutrinos with broad sensitivity to neutrino oscillation parameters in a single experiment. The focus of the program will be the explicit demonstration of leptonic CP violation, if it exists, by precisely measuring the asymmetric oscillations of muon-type neutrinos and antineutrinos into electron-type neutrinos and antineutrinos. Siting the far detector deep underground will provide exciting additional research opportunities in nucleon decay, neutrino astrophysics and studies of neutrino bursts from supernovae occurring in our galaxy.

This is where the common introductory remarks end. You could add some additional information here about the volume itself, e.g.,

This introductory volume of the LBNF/DUNE Conceptual Design Report provides an overview of DUNE's science program (Chapter 2) and the technical designs of the facilities and the detectors (Chapter 3). It also describes the LBNF and DUNE organization and management structures (Chapter 4) and the strategy that is being developed to construct, install and commission the conventional and experimental facilities in accordance with the requirements set out by the P5 report of 2014, which, in turn, is in line with the CERN European Strategy for Particle Physics (ESPP) of 2013.

cite these documents

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Chapter 2

DUNE Science

2.1 Overview

This chapter summarizes DUNE's potential for achieving its core physics objectives based on the current experimental landscape, scenarios for staging LBNF and DUNE, and the technical capabilities of DUNE at each stage. The objectives include topics in long-baseline neutrino physics, nucleon decay, supernova neutrinos, astrophysics and short-baseline physics. A detailed description of the physics objectives of DUNE is provided in Volume 2 of the CDR.

For reasons described later in Chapter 5, the DUNE far detector (FD) will be built as four 10-kt modules, which will come online over the course of several years. The staged program with the FD rapidly growing in mass will enable an early start of the science, initially primarily focused at the observation of natural sources neutrinos, the searches for nucleon decays and the measurements of backgrounds. Soon after the long-baseline neutrino beam at FNAL will start operation sending neutrinos over the 1300 km baseline. The near detector (ND) will likely start operations after beamline operation is already ongoing. Without any ND constraints, the neutrino flux will be moderately well constrainted in the early stages of the experiment, however this will not significantly impact the early physics programme since the statistical errors in the FD will dominate in most channels. It is assumed that data sets collected during earlier stages will be reanalyzed with new assumptions, so that each improvement in systematic uncertainty is applied to the full exposure up to that point. Eventually, the LBNF beam power is expected to be upgraded from $\sim$1 MW to $\sim$2 MW enabling high statistics to be collected in the FD. Here, the ND will provide the necessary capability to reduce systematic errors at the level where the full power of the beam coupled to the large FD mass will yield the ultimate sensitivities of the experiment.

2.2 Long-Baseline neutrino oscillation physics

The DUNE science reach is described in details in Volume 2: The Physics Program for DUNE at LBNF as a function of exposure. The exposure is a measure of the amount of data collected and is expressed in units of kt · MW · year. For instance, an exposure of 300 kt · MW · year corresponds to seven years of data (3.5 years in neutrino mode plus 3.5 years in antineutrino mode) with a 10-kt detector and a 1.07 MW beam.

For the estimate of the sensitivity of DUNE as a function of real time for the first 10 years of operation, a staging plan is assumed which allows to determine the reachable exposure as a function of the running years. For the discussions below, the following staging plan has been assumed:

- Year 1: 10 kt FD mass; 1.07 MW beam power; No ND constraints (assume 5% signal systematic)
- Year 2: Add second 10-kt FD module, for a total FD mass of 20 kt
- Year 3: Add third 10-kt FD module, for a total FD mass of 30 kt; Include constraints from preliminary ND data analysis (assume 3% signal systematic)
- Year 4: Add fourth 10-kt FD module, for a total FD mass of 40 kt
- Year 5: Include constraints from a full ND data analysis (assume 2% signal systematic)
- Year 7: Upgrade of beam power to 2.14 MW

It is assumed that previous data sets can be reanalyzed with new assumptions, so each improvement in systematic uncertainty is applied to the full exposure up to that point.

The 1300-km baseline establishes one of DUNE's key strengths: sensitivity to the matter effect. This effect leads to a discrete asymmetry in the $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities, the sign of which depends on the presently unknown mass hierarchy (MH). At 1300 km this asymmetry is approximately $\pm 40\%$ in the region of the peak flux; this is larger than the maximal possible CP-violating asymmetry associated with $\delta_{\rm CP}$, meaning that both the MH and $\delta_{\rm CP}$ can be determined unambiguously with high confidence within the same experiment.

In detail, the sensitivity of DUNE depends on the actual values of poorly known mixing parameters (mainly $\delta_{\rm CP}$ and $\sin^2\theta_{23}$), as well as the true value of the MH itself. The discrimination between the two MH hypotheses is characterized as a function of the *a priori* unknown true value of $\delta_{\rm CP}$ by considering the difference, denoted $\Delta\chi^2$, between the $-2\log\mathcal{L}$ values calculated for a data set with respect to these hypotheses, considering all possible values of $\delta_{\rm CP}$[1]. In terms of this test statistic,

[1]For the case of the MH determination, the usual association of this test statistic with a χ^2 distribution for one degree of freedom is incorrect; additionally the assumption of a Gaussian probability density implicit in this notation is not exact. The discussion in Chapter 3 of Volume 2: The Physics Program for DUNE at LBNF provides a brief description of the statistical considerations.

the MH sensitivity of DUNE with an exposure of 300 kt · MW · year is illustrated in Figure 2.1 for the case of normal hierarchy and the current best fit value of $\sin^2\theta_{23} = 45$

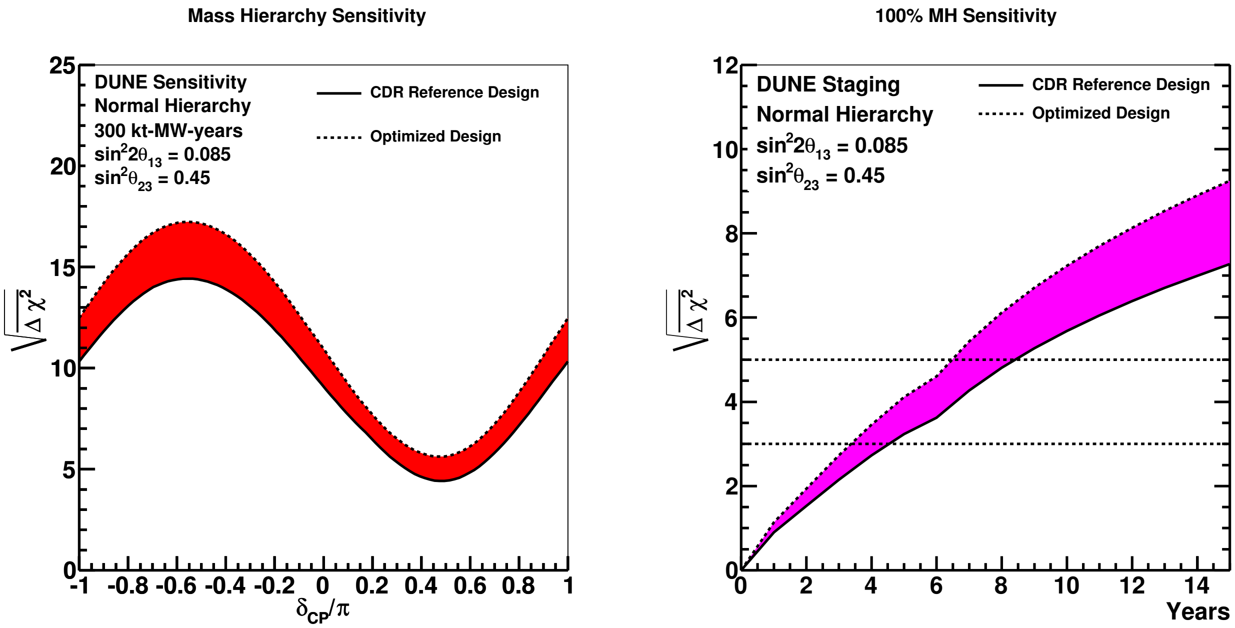

Figure 2.1: The square root of the mass hierarchy discrimination metric $\Delta\chi^2$ is plotted as a function of the unknown value of $\delta_{\rm CP}$ for an exposure of 300 kt · MW · year (left). The minimum significance — the lowest point on the curve on the left - with which the mass hierarchy can be determined for all values of $\delta_{\rm CP}$ as a function of years of running under the staging plan described in the text (right). The shaded region represents the range in sensitivity due to potential variations in the beam design.

Across the overwhelming majority of the parameter space for the mixing parameters that are not well known (mainly $\delta_{\rm CP}$ and $\sin^2\theta_{23}$), DUNE's determination of the MH will be definitive, but even for unfavorable combinations of the parameter values, a statistically ambiguous outcome is highly unlikely. The least favorable scenario corresponds to a true value of $\delta_{\rm CP}$ in which the MH asymmetry is maximally offset by the leptonic CP asymmetry, and where, independently, $\sin^2\theta_{23}$ takes on a value at the low end of its experimentally allowed range. For this scenario, studies indicate that with the DUNE staging plan outlined earlier, the DUNE LArTPC, operating for 8.5 years in the 80-GeV 1.07-MW (reference design) beam, can — in a typical data set — distinguish between normal and inverted hierarchy with $|\Delta\chi^2| = \overline{|\Delta\chi^2|} = 25$. This corresponds to a $\geq 99.9996\%$ probability of determining the correct hierarchy. In $> 97.5\%$ of data sets, DUNE will measure $|\Delta\chi^2| > 9$ in this scenario, where measuring $|\Delta\chi^2| = 9$ with an expected value of 25 corresponds to a significance in excess of three Gaussian standard deviations. Improvements to the beam design can lower the exposure needed to reach this level of sensitivity from 400 kt · MW · year to around 230 kt · MW · year. The dependence of the mass hierarchy sensitivity on systematics is still under evaluation, but current studies indicate a weak dependence on systematic uncertainties. This indicates that a measurement of the unknown neutrino mass hierarchy with very high precision can be carried out during the first few years of operation with an optimized beamline design.

Concurrent analysis of the corresponding atmospheric-neutrino samples in an underground detector will improve the precision and speed with which the MH is resolved.

With regard to the search for CP-violation using the ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation channels, the DUNE program has two somewhat distinct objectives. First, DUNE aims to make a precise determination of the value of $\delta_{\rm CP}$ within the context of the standard three-flavor mixing scenario described by the PMNS neutrino mixing matrix. Second, and perhaps more significantly, DUNE aims to observe a signal for leptonic CP violation, independent of the underlying nature of neutrino oscillation phenomenology. Within the standard three-flavor mixing scenario, such a signal will be observable, provided $\delta_{\rm CP}$ is not too close to either of the values for which there is no CP violation (zero and π). Together, the pursuit of these two goals provides a thorough test of the standard three-flavor scenario.

Figure 2.2 shows the expected sensitivity to CP violation as well as the 1σ resolution for $\delta_{\rm CP}$ as a function of exposure. The exposure in detector mass (kiloton) $\times$ beam power(MW) $\times$ time (years) required to measure $\delta_{\rm CP} = 0$ with a precision better than $10°$ ranges from 290 to 450 $\mathrm{kt \cdot MW \cdot year}$ depending on the beam design. A fully realized DUNE operating with multi-megawatt beam power can eventually achieve a precision comparable to the current precision on the CP phase in the CKM matrix in the quark sector (5%).

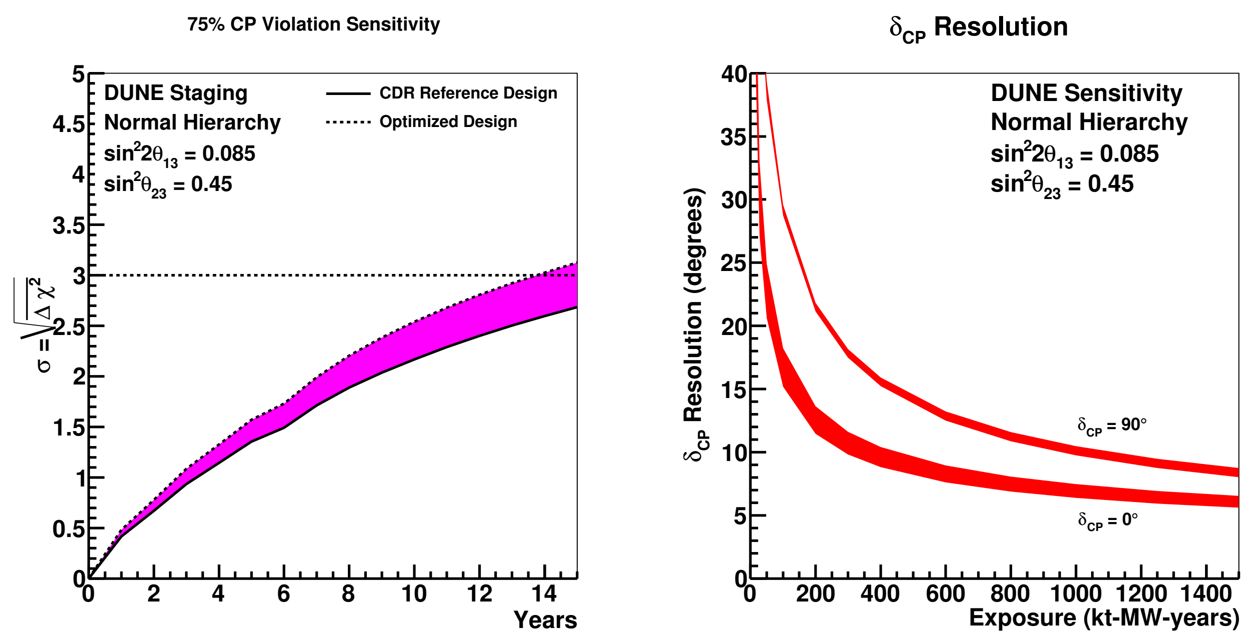

Figure 2.2: The significance with which CP violation can be determined for 75% of $\delta_{\rm CP}$ values as a function of exposure in years using the proposed staging plan outlined in this chapter (left). The expected 1σ resolution for $\delta_{\rm CP}$ as a function of exposure in $\mathrm{kt \cdot MW \cdot year}$ (right). The shaded region represents the range in sensitivity due to potential variations in the beam design. This plot assumes normal mass hierarchy.

To reach 5σ sensitivity for 50% of the range of $\delta_{\rm CP}$, a DUNE exposure in the range of 550 to 810 $\mathrm{kt \cdot MW \cdot year}$ is needed. The range of exposures corresponds to potential variations in the beam design, with the highest exposures corresponding to the reference beam design. Table 2.1 summarizes the exposures needed to achieve specific oscillation physics milestones. The sensitivities and exposures calculated are for the current best fit values of the known neutrino mixing parameters. Changes in the value of θ_{23} impact CP violation and mass hierarchy sensitivities the most, as discussed in Volume 2, and can reduce or increase the exposure needed to reach discovery potential for CP violation over a significant fraction of $\delta_{\rm CP}$ values. In addition, potential improvements in beamline geometry, focusing and target element designs that can significantly lower the exposure required for CP violation discovery potential as demonstrated in Table 2.1. Several such potential improvements are discussed in CDR Volume 2 and Volume 3. A highly capable near neutrino detector is required to control systematic uncertainties at a level lower than the statistical uncertainties in the far detector needed to reach this level of sensitivity. No experiment can provide coverage at 100% of $\delta_{\rm CP}$ values, since CP violation effects vanish as $\delta_{\rm CP} \to 0$ or π.

In long-baseline experiments with ν_μ beams, the magnitude of ν_μ disappearance and ν_e appearance signals is proportional to $\sin^2 2\theta_{23}$ and $\sin^2\theta_{23}$, respectively, in the standard three-flavor mixing scenario. Current ν_μ disappearance data are consistent with close to maximal mixing, $\theta_{23} = 45°$. To obtain the best sensitivity to both the magnitude of its deviation from 45° as well as its sign (θ_{23} octant), a combined analysis of the two channels is needed [**?**]. As demonstrated in Volume 2, a 40-kt DUNE detector with sufficient exposure will be able to resolve the θ_{23} octant at the 3σ level or better for θ_{23} values less than 43° or greater than 48°. A fully realized DUNE can measure θ_{23} with a precision of 1° or less, even for values within a few degrees of 45°.

To summarize, DUNE long-baseline program will comple our understanding of the oscillation phenomenology. DUNE has great prospects to discover CP-violation or in absence of effect, set stringent limits on the allowed values of the $\delta_{\rm CP}$ phase. DUNE will also determine the neutrino mass hierarchy with better than a 5σ C.L. Table 2.1 summarizes the exposures needed to reach these oscillation physics milestones. The numbers are for normal hierarchy using the current best fit values of the known oscillation parameters. The two columns on the right are for different beam design assumptions.

Table 2.1: The exposure in mass (kt) × proton beam power (MW) × time (years) needed to reach certain oscillation physics milestones. The numbers are for normal hierarchy using the current best fit values of the known oscillation parameters. The two columns on the right are for different beam design assumptions.

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
$1°$ θ_{23} resolution ($\theta_{23} = 42°$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
$10°$ resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

2.3 Nucleon Decay Physics Motivated by Grand Unified Theories

The DUNE far detector will significantly extend lifetime sensitivity for specific nucleon decay modes by virtue of its high detection efficiency relative to water Cherenkov detectors and its low background rates. As an example, DUNE has enhanced capability for detecting the $p \to K^+\bar{\nu}$ channel, where lifetime predictions from supersymmetric models extend beyond, but remain close to, the current (preliminary) Super-Kamiokande limit of $\tau/B > 5.9 \times 10^{33}$ year (90% CL) from a 260-kt · year exposure [**?**][2]. The signature for an isolated semi-monochromatic charged kaon in a LArTPC is distinctive, with multiple levels of redundancy.

The DUNE LArTPC far detectors deep underground will reach a limit of 3×10^{34} year after 10-12 years of operation (Figure 2.3) depending on the deployment scenario, and would see nine events with a background of 0.3 should τ/B be 1×10^{34} year, just beyond the current limit. A 40-kt detector will improve the current limits by an order of magnitude after running for two decades. Even a 10-kt detector would yield an intriguing signal of a few events after a ten-year exposure.

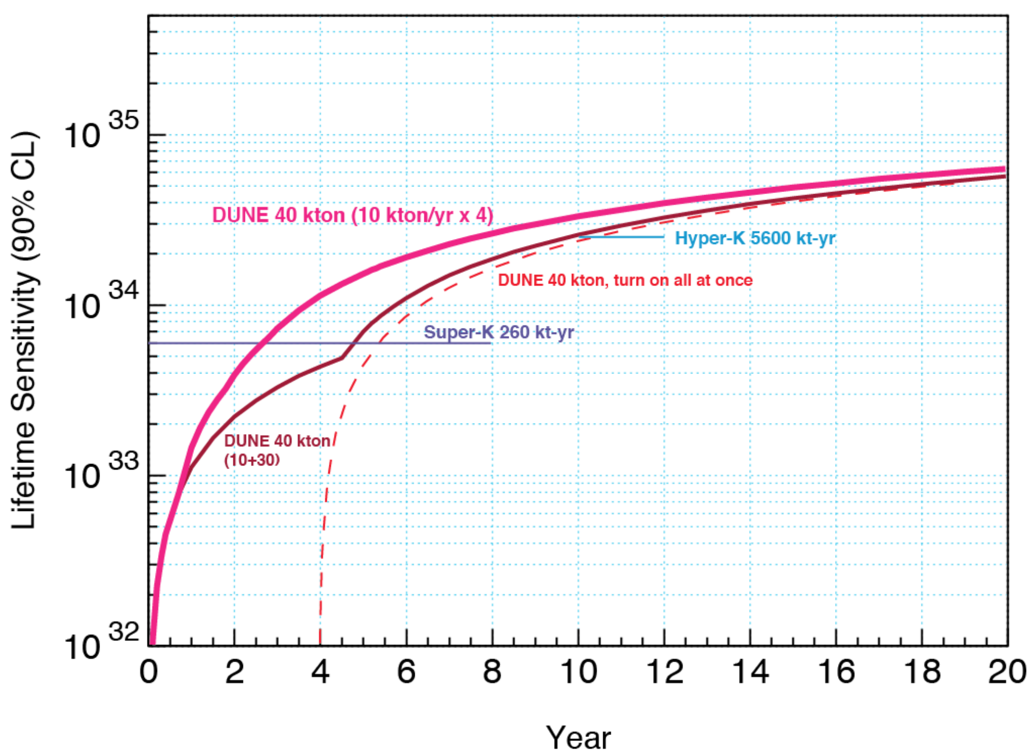

Figure 2.3: Sensitivity to the decay $p \to K^+\bar{\nu}$ as a function of time for different DUNE LArTPC module deployment strategies. For comparison, the current limit from SK is also shown, as well as the projected limit from the proposed Hyper-K experiment with 5600 kt · year of exposure. The limits are at 90% C.L., calculated for a Poisson process including background, assuming that the detected events equal the expected background.

[2] The lifetime shown here is divided by the branching fraction for this decay mode, τ/B, and as such is a *partial lifetime*.

Supersymmetric GUT models in which the $p \to K^+\overline{\nu}$ channel mode is dominant also favor other modes involving kaons in the final state, thus enabling a rich program of searches for nucleon decay in the DUNE LArTPC detectors.

2.4 Supernova-Neutrino Physics and Astrophysics

The neutrinos from a core-collapse supernova are emitted in a burst of a few tens of seconds duration, with about half in the first second. Energies are in the range of a few tens of MeV, and the luminosity is divided roughly equally between the three known neutrino flavors. Currently, experiments worldwide are sensitive primarily to electron antineutrinos ($\bar{\nu}_e$), with detection through the inverse-beta decay process on free protons[3], which dominates the interaction rate in water and liquid-scintillator detectors. Liquid argon has a unique sensitivity to the electron-neutrino (ν_e) component of the flux, via the absorption interaction on ^{40}Ar as follows:

$$\nu_e + {}^{40}\mathrm{Ar} \;\; \to \;\; e^- + {}^{40}\mathrm{K}^*$$

This interaction can be tagged via the coincidence of the emitted electron and the accompanying photon cascade from the ^{40}K* de-excitation. About 3000 events would be expected in a 40-kt fiducial mass liquid argon detector for a supernova at a distance of 10 kpc. In the neutrino channel the oscillation features are in general more pronounced, since the ν_e spectrum is always significantly different from the ν_μ (ν_τ) spectra in the initial core-collapse stages, to a larger degree than is the case for the corresponding $\bar{\nu}_e$ spectrum. Detection of a large neutrino signal in DUNE would help provide critical information on key astrophysical phenomena such as

- the neutronization burst
- formation of a black hole
- shock wave effects
- shock instability oscillations
- turbulence effects

In addition to providing unprecedented information on the mechanics of the supernova explosion, observation of a core-collapse supernova in DUNE will also enable searches for numerous types of new physics including various Goldstone bosons (e.g., Majorons), neutrino magnetic moments, new gauge bosons (“dark photons”), “unparticles” and extra-dimensional gauge bosons.

[3] This refers to neutrino interactions with the nucleus of a hydrogen atom in H_2O in water detectors or in hydrocarbon chains in liquid scintillator detectors.

2.5 Precision Measurements with the DUNE Near Detector

The DUNE near neutrino detector (ND) will provide precision measurements of neutrino interactions, which are essential for controlling the systematic uncertainties in the long-baseline oscillation physics program. The near detector will include argon targets and will measure the absolute flux and energy-dependent shape of all four neutrino species, ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$, to accurately predict for each species the far/near flux ratio as a function of energy. It will also measure the four-momenta of secondary hadrons, such as charged and neutral mesons, produced in the neutral and charged current interactions that constitute the dominant backgrounds to the oscillation signals.

The near detector will also be the source of data for a rich program of neutrino-interaction physics in its own right. For an integrated beam intensity of 1×10^{20} protons-on-target at 120 GeV, the expected number of events per ton is 240,000 (85,000) ν_μ ($\bar{\nu}_\mu$) charged current and 90,000 (35,000) neutral current interactions in the ν ($\overline{\nu}$) beam. These numbers correspond to 10^7 neutrino interactions per year for the range of beam configurations and near detector designs under consideration. Measurement of fluxes, cross sections and particle production over a large energy range of 0.5 GeV to 50 GeV are the key elements of this program. These events will also help constrain backgrounds to proton decay signals from atmospheric neutrinos. Furthermore, very large samples of events will be amenable to precision reconstruction and analysis, and will be exploited for sensitive studies of electroweak physics and nucleon structure, as well as for searches for new physics in unexplored regions, such as heavy sterile neutrinos, high-Δm^2 oscillations, light Dark Matter particles, and so on.

2.6 Summary

This chapter touches only briefly on the most prominent portion of the full suite of physics opportunities enabled by DUNE. Volume 2: The Physics Program for DUNE at LBNF includes a more detailed discussion and covers topics that were omitted here in the interest of brevity and focus. In Chapter 5 progress toward DUNE physics milestones is addressed, based on potential scenarios for the deployment of DUNE detector modules, the beamline and PIP-II implementations.

In summary, the primary science goals of DUNE are drivers for the advancement of particle physics. The questions being addressed are of wide-ranging consequence: the origin of flavor and the generation structure of the fermions (i.e., the existence of three families of quark and lepton flavors), the physical mechanism that provides the CP violation needed to generate the Baryon Asymmetry of the Universe (BAU), and the high-energy physics that would lead to the instability of matter. Achieving these goals requires a dedicated, ambitious and long-term program. No other proposed long-baseline neutrino oscillation program with the scientific scope and sensitivity of DUNE is as advanced in terms of engineering development and project planning. Implementation of a staged program with a far detector of even modest size in the initial stage (e.g., 10 kt) will enable exciting physics in the intermediate term, including a definitive mass hierarchy determination and a measurement of the CP phase without ambiguities, while providing the fastest route toward achieving the full range of DUNE's science objectives. Should DUNE find that the CP phase is not zero or π, it will have found strong indications ($> 3\sigma$) of leptonic CP violation.

The DUNE experiment is a world-leading international physics experiment, bringing together the global neutrino community as well as leading experts in nucleon decay and particle astrophysics to explore key questions at the forefront of particle physics and astrophysics. The highly capable beam and detectors will enable a large suite of new physics measurements with potential groundbreaking discoveries.

Chapter 3

Technical Designs

3.1 LBNF Project

LBNF will provide facilities at Fermilab and at SURF to enable the scientific program of DUNE. These facilities are geographically separated into the Near Site Facilities, those to be constructed at Fermilab, and the Far Site Facilities, those to be constructed at SURF.

LBNF is managed through a Project Office where management and functions common to both Far Site and Near Site Facilities occur. LBNF coordinates requirements and interfaces with the DUNE Project through the Experiment-Facility Interface Group as well as working teams comprised of members of both projects.

why is this here? it's covered in org/mgmt

3.1.1 Near Site Facilities

The scope of LBNF at Fermilab is provision of the beamline plus the conventional facilities (CF) for this beamline as well as for the DUNE near detector. The layout of these facilities is shown in Figure 3.1. The science requirements as determined by the DUNE Collaboration drive the performance of the beamline and near detector, which then provide requirements for the components, space, and functions necessary to construct, install, and operate the beamline and near detector. ES&H and facility operations requirements (i.e., *programmatic* requirements) also provide input to the design.

The beamline is designed to provide a neutrino beam of sufficient intensity and appropriate energy range to meet the goals of DUNE for long-baseline neutrino oscillation physics. The design is a conventional, horn-focused neutrino beamline. The components of the beamline will be designed to extract a proton beam from the Fermilab Main Injector (MI) and transport it to a target area

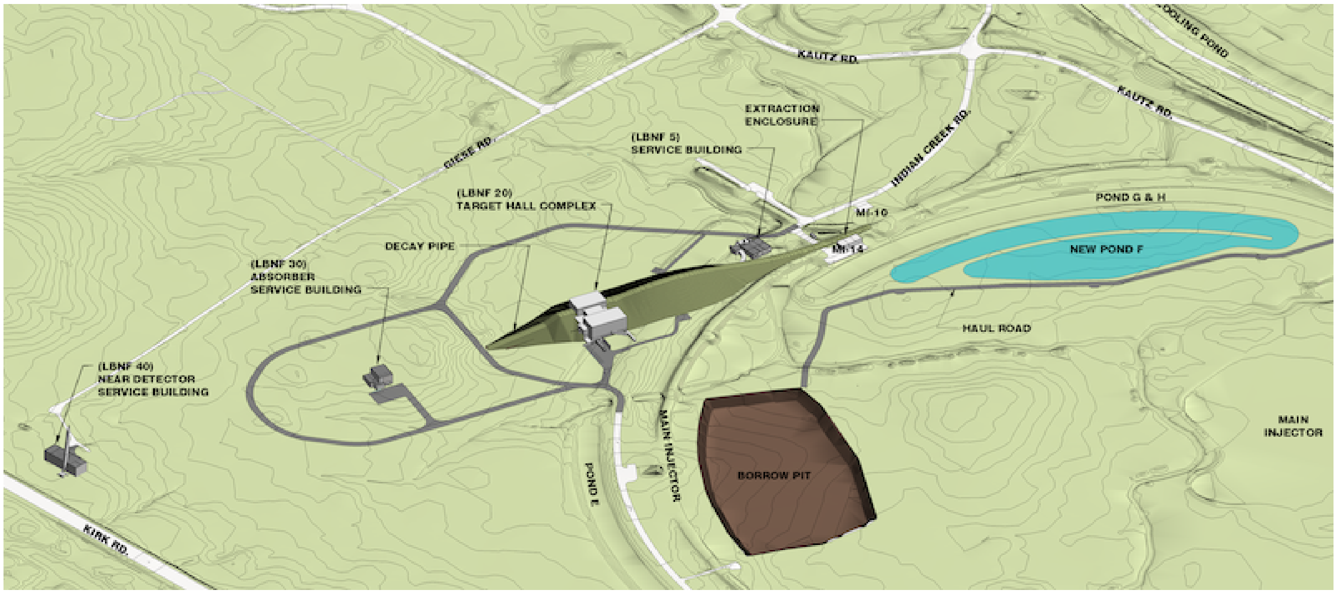

Figure 3.1: Layout of LBNF Near Site

where the collisions generate a beam of charged particles.

add something about decaying to neutrinos in the decay pipe?

The facility is designed for initial operation at proton-beam power of 1.2 MW, with the capability to support an upgrade to 2.4 MW. The plan is for twenty years of operation, while the lifetime of the Beamline Facility, including the shielding, is for thirty years. It is conservatively assumed that operations during the first five years will be at 1.2-MW and the remaining fifteen years at 2.4 MW. The experience gained from the various neutrino projects has contributed extensively to the reference design. In particular, the NuMI beamline serves as the prototype design. Most of the subsystem designs and the integration between them follow, to a large degree, from previous projects.

The proton beam will be extracted at a new point at MI-10. After extraction, this primary beam will establish a horizontally straight compass heading west-northwest toward the far detector, but will be bent upward to an apex before being bent downward at the appropriate angle. The primary beam is designed to be above grade to minimize expensive, underground construction; this also significantly enhances ground-water radiological protection. The design requiresconstruction of an earthen embankment, or hill, whose dimensions are commensurate with the bending strength of the dipole magnets required for the beamline.

The target marks the transition from the intense, narrowly directed proton beam to the more diffuse, secondary beam of particles that in turn decay to produce the neutrino beam. After collection and focusing, the pions and kaons that did not initially decay need a long, unobstructed volume in which to do so. This decay volume in the reference design is a pipe of circular cross section with its diameter and length optimized such that decays of the pions and kaons result in neutrinos in the energy range useful for the experiment. The decay volume is followed immediately by the absorber, which removes the remaining beam hadrons.

Radiological protection is integrated into the LBNF beamline reference design in two important ways. First, shielding is optimized to reduce exposure of personnel to radiation dose and to minimize radioisotope production in ground water within the surrounding rock. Secondly, the handling and control of tritiated ground water produced in or near the beamline drives many aspects of the design.

Beamline CF includes an enclosure connecting to the existing Main Injector at MI-10, concrete underground enclosures for the primary beam, targetry, horns, absorber, and related technical support systems. Service buildings will be constructed to provide support utilities the primary proton beam at LBNF 5 and to support the absorber at LBNF 30 (shown in Figure 3.1). The enclosure for the Target Hall will be both below and above grade

‘both below and above grade’ is not clear; confusing

and is identified as LBNF 20. Utilities will be extended from nearby existing services, including power, domestic and industrial water, sewer, and communications.

Near Detector CF includes a small muon alcove area in the Beamline Absorber Hall and a separate underground Near Detector Hall that houses the near detector. A service building called LBNF 40 with two shafts to the underground supports the near detector. The underground hall is sized for the reference Near Neutrino Detector (NND).

just reference near detector is better, I think.

3.1.2 Far Site Facilities

The scope of LBNF at SURF includes both conventional facilities (CF) and cryogenic infrastructure to support the DUNE far detector. Figure 3.2 shows the layout of the underground caverns that will house the detector modules. The requirements derive from DUNE Collaboration science requirements, which drive the space and functions necessary to construct and operate the far detector. ES&H and facility operations (programmatic) requirements also provide input to the design. The far detector is modularized into four 10-kt fiducial mass detectors

determine if reference should be for total mass instead of fiducial

. The four caverns and the services to the caverns will be as similar to one another as possible for efficiency in design and construction, as well as operation.

The Far Site CF includes design and construction for facilities both on the surface and underground. The underground conventional facilities includes new excavated spaces at the 4850L for the detector, utility spaces for experimental equipment, utility spaces for facility equipment, drifts

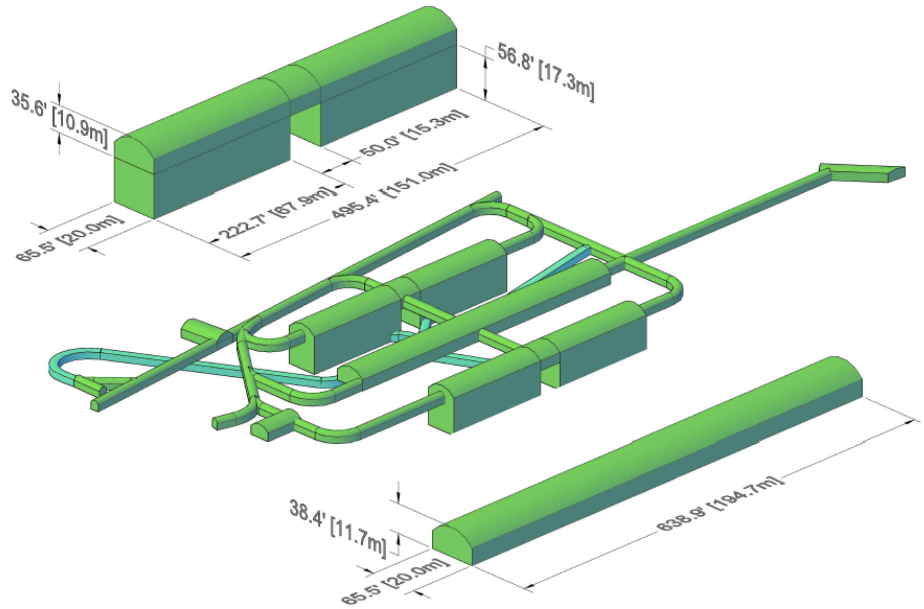

Figure 3.2: LBNF Far Site cavern configuration

fig:cav-

for access, as well as construction-required spaces. Underground infrastructure provided by CF for the experiment includes power to experimental equipment, cooling systems and cyberinfrastructure. Underground infrastructure necessary for the facility includes domestic (potable) water, industrial water for process and fire suppression, fire detection and alarm, normal and standby power systems, a sump pump drainage system for native and leak water around the detector, water drainage to the facility-wide pump discharge system, and cyberinfrastructure for communications and security. In addition to providing new spaces and infrastructure underground, CF will enlarge and provide infrastructure in some existing spaces, such as the access drifts from the Ross Shaft to the new caverns. New piping will be provided in the shaft for cryogens (gas argon transfer line and the compressor suction and discharge lines) and domestic water as well as power conduits for normal and standby power and cyberinfrastructure.

SURF currently has many surface buildings and utilities, some of which will be utilized for LBNF. The scope of the above-ground CF includes only that work necessary for LBNF, and not for the general rehabilitation of buildings on the site, which remains the responsibility of SURF. Electrical substations and distribution will be upgraded to increase power and provide standby capability for life safety. Additional surface scope includes a small control room in an existing building and a new building to support cryogen transfer from the surface to the underground near the existing Ross Shaft.

To reduce risk during the construction and installation period, several SURF infrastructure operations/maintenance activities are included as early activities in the LBNF Project. These include completion of the Ross Shaft rehabilitation, rebuilding of hoist motors, and replacement of the Oro Hondo fan; if not addressed, this aging infrastructure could limit or remove access to the underground if equipment failed.

The scope of the LBNF cryogenics infrastructure includes the design, fabrication, and installation of four cryostats to contain the liquid argon (LAr) and the detector components. It also includes a comprehensive cryogenic system that meets the performance requirements for purging, cooling and filling the cryostats, for achieving and maintaining the LAr temperature, and for purifying the LAr outside the cryostats.

Each cryostat will be composed of a free-standing steel-framed structure, to be constructed in its individual cavern, with a membrane cryostat installed inside. The interior dimension of the cryostat design is 15.1 m width, 14.0 m height and 62.0 m length and it has a total LAr mass capacity of 17.1 kt . Each cryostat will include a stainless-steel liner to contain the liquid cryogen. The pressure loading of the liquid cryogen is transmitted through rigid foam insulation to the surrounding structural steel frame which provides external support for the membrane. The membrane system will provide full containment of the LAr. The hydrostatic load of the LAr in the cryostat design is carried by the steel frame on sides and bottom. Everything else within the cryostat (TPC planes

TPCs haven't been introduced; maybe "detector elements"

, electronics, sensors, cryogenic- and gas-plumbing connections) will be supported by the steel top plate

check this is true with steel frame

. All piping and electrical penetrations into the interior of the cryostat will be made through this top plate to minimize the potential for leaks.

Cryogenic system components will be located on the surface or within the cavern. The cryogen receiving station will be located on the surface near the Ross Shaft to allow for receipt of LAr deliveries for the initial filling period, as well as a buffer volume to accept liquid argon during the extended fill period. A large vaporizer at the surface will vaporize the liquid argon from the storage dewar prior to the argon gas being transferred by uninsulated piping down this shaft.

A liquid nitrogen dewar also located at the surface will be used to accept nitrogen deliveries for the initial charging and startup of the nitrogen refrigerator, as well as for pressure control of the LAr storage dewar. A large vaporizer for the nitrogen circuit will vaporize nitrogen to nitrogen gas for feeding the compressors of the nitrogen refrigerator. Four compressors, the only refrigerator components on the surface, and supporting systems will be located in a compressor building near the Ross Shaft and cryogen receiving area. The compressors discharge high pressure nitrogen gas into pipes that will run down the shaft. The compressors will be located on the surface because the electrical power requirement and cooling requirement is much less than for similar equipment at the 4850L.

The detector cavern at 4850L will contain the rest of the nitrogen refrigerator, liquid nitrogen vessels, argon condensers, external liquid argon recirculation pumps, and filtration equipment. Filling each cryostat with LAr in a reasonable period of time is a driving factor for the refrigerator and condenser sizing. Each cryostat will have its own argon recondensers, argon-purifying equipment and overpressure protection system, also located in the central utility cavern. Recirculation pumps will be placed outside of each cryostat to circulate liquid from the bottom of the tank through the purifier.

3.2 The DUNE Detectors

The DUNE detectors to be installed at SURF (the far location) and FNAL (the near location) will enable the scientific program of DUNE. The detector requirements derive from these DUNE science goals.

3.2.1 The Far Detector

The Far Detector (FD) will be located deep underground at the 4850L and have a fiducial mass of 40-kt to perform sensitive studies of long-baseline oscillations with a 1300-km baseline as well as a rich astroparticle physics programme and nucleon decay searches. The FD will be composed of four similar modules, each instrumented as a Liquid Argon Time Projection Chamber (LArTPC). The concept of the LArTPC provides excellent tracking and calorimetry performance, hence it is ideal for massive neutrino detectors such as DUNE's, which require a high signal efficiency and effective background discrimination, an excellent capability to identify and precisely measure neutrino events over a wide range of energies, and an excellent reconstruction of the kinematical properties with a high resolution. The full imaging of events will allow study of neutrino interactions and other rare events in an unprecedented way.

to an unprecedented level of precision?

The huge mass will allow collectiopn of sufficient statistics for precision studies, as discussed in Chapter 2.

The LArTPC, pioneered in the context of the ICARUS project, is a mature technology. It is the outcome of several decades of R&D executed worldwide. Nonetheless, the size of a single 10-kt DUNE module represents an extrapolation by approximately one order of magnitude compared to the largest operated detector, the ICARUS T600. To address this challenge, DUNE is developing two far detector options, the reference design and the alternative design, and is engaged in a comprehensive prototyping effort. At this stage, the development of two FD options is a strength and an added-value

asset or advantage?

made possible by the merging of the worldwide neutrino community into DUNE. The two detector concepts are illustrated in Figure 3.3.

Interactions in LAr produce ionization charge and scintillation light. The charge is drifted with a constant electric field away from the cathode plane and towards the segmented anode plane.

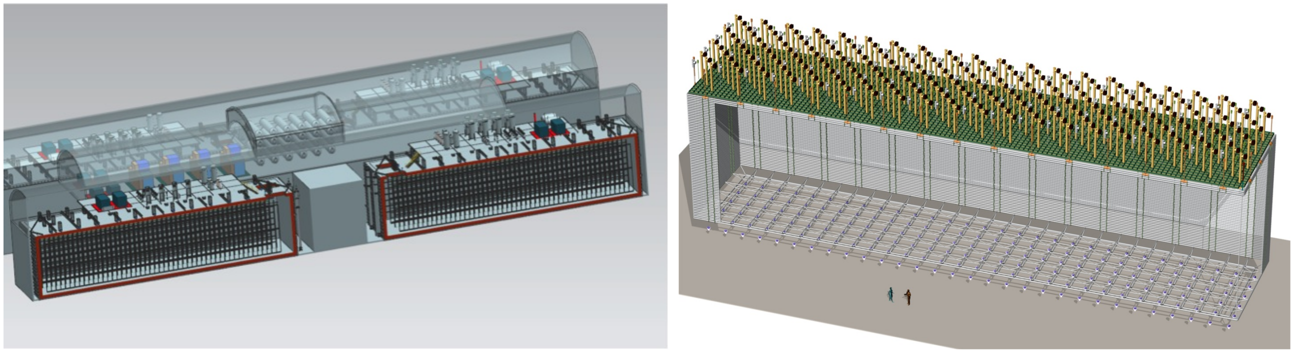

Figure 3.3: 3D models of two 10-kt detectors using the single-phase reference design (left) and the dual-phase alternative design (right) for the DUNE far detector to be located at 4850L. fig:FarD

Maury had comments on this; I think it's that the negative charge, i.e., ionization electrons that are drifted away from cathode, not charge in general

The prompt scintillation light, detected by photo-detectors, provides the absolute time of the event. The reference design adopts a single-phase readout, where the readout anode is composed wire planes in the LAr volume. In the alternative design, the dual-phase approach is considered, in which the ionization charges are extracted, amplified and detected in gaseous argon (GAr) above the liquid surface. The dual-phase design would allow for a finer readout pitch (3 mm), a lower detection-energy threshold, and better pattern reconstruction of the events. The photon-detection scheme used in both designs is similar.

Anne changed sentence

The 10-kt reference design TPC is described in Chapter 4 of Volume 4: The DUNE Detectors at LBNF. Its active volume is 12 m high, 14.5 m wide and 58 m long, instrumented with APAs, which are 6 m high and 2.3 m in width, and CPAs, 3 m high by 2.5 wide. Vertical stacks of two APAs and four CPAs instrument the 12 m height of the active volume. The 12.5-m width of the detector is spanned by three stacks of APAs and two stacks of CPAs in an APA:CPA:APA:CPA:APA arrangement, resulting in four 3.6 m drift volumes, while the 58-m length of the active volume is spanned by 25 such stack arrangements placed edge to edge. Hence a 10-kt far detector module consists of 150 APAs and 200 CPAs. The CPAs are held a -180 kV, such that ionization electrons drift a maximum distance of 3.6 m in the electric field of $500\,\mathrm{V\,cm^{-1}}$. The highly modular nature of the detector design allows for manufacturing to be distributed across a number of sites.

A comprehensive prototyping strategy for both designs is actively pursued. The reference design, closer to the original ICARUS design, is currently being validated in the 35-t prototype LAr detector at Fermilab. The alternative design, representing a novel approach, has been proven on several small-scale prototypes. Presently a 20-t dual-phase prototype with dimensions $3\times1\times1\ \mathrm{m}^3$ is being constructed at CERN (WA105), and should be operational in 2016. The ultimate validation of the engineered solutions for both designs of the FD is foreseen at the CERN Neutrino Platform around 2018, is it a place or a program?

where full-scale engineering prototypes will be assembled and commissioned. Following this milestone, a test-beam data campaign will be executed to collect a large sample of charged-particle interactions in order to study the response of the detector with high precision. A comprehensive list of synergies between the reference and alternative designs has been identified (Chapter 6 of Volume 4: The DUNE Detectors at LBNF). Common solutions for DAQ, electronics, HV feedthroughs, and so on, will pursued and implemented, independent of the details of the TPC design. The ongoing and planned efforts will provide the ideal environment to exploit such synergies and implement common solutions. There is recognition that the LArTPC technology will continue to evolve with (1) the large-scale prototypes at the CERN Neutrino Platform and the experience from the Fermilab SBN program, and (2) the experience gained during the construction and commissioning of the first 10-kt module. The staged approach with the deployment of consecutive modules will enable an early science program while allowing implementation of improvements and developments during the experiment's lifetime. The strategy for implementing the far detector is presented in Chapter v1ch:strategy 5.

3.2.2 The Near Detector

We need to distinguish between near detector and near neutrino detector. I think the ND is NND+BLM+DAQ. Is this right?

To meet the systematic precision needed to fulfill the DUNE science objectives, the near detector must thoroughly characterize the neutrino beam at the source, where it is composed of both muon- and electron-flavored neutrinos and antineutrinos.

Did I get this right?

Additionally, it must precisely measure the cross sections and the particle yields of various processes that compose neutrino events. Its primary role is therefore collection of neutrino-interaction statistics to an uprecedented level. This wealth of fundamental neutrino-interaction measurements will satisfy important secondary scientific goals of the DUNE Collaboration. The reference design for the neutrino near detector (NND) design is the NOMAD-inspired fine-grained tracker (FGT), illustrated in Figure fig:FGT schematic 3.4. The subsystems of the NND include a central straw-tube tracker and an electromagnetic calorimeter embedded in a 0.4-T dipole field. The steel of the magnet yoke will be instrumented with muon identifiers. The strategy for implementation of the Near Detector

ND or NND?

is presented in Chapter v1ch:strategy 5.

The above is a rewrite of the following pgraph (so of course I propose dropping the following). Anne

The spectrum and flavor composition of the neutrino beam will be measured with high precision in order to reach the ultimate sensitivity for the long-baseline neutrino oscillation studies. The separation between fluxes of neutrinos and antineutrinos requires a magnetized neutrino detector to charge-discriminate electrons and muons produced in the neutrino charged-current interactions. This is the primary role of the DUNE near detector system, however, being exposed to an intense flux of neutrinos will also provides the opportunity to collect an unprecedentedly high statistics of neutrino interactions for an extended science program. The near detector will therefore provide an opportunity for a wealth of fundamental neutrino interaction measurements, which are an important part of the secondary scientific goals of the DUNE collaboration. The reference design for the neutrino near detector (NND) design is the NOMAD-inspired fine-grained tracker (FGT), illustrated in Figure 3.4. The subsystems of NND comprise a central straw-tube tracker and an electromagnetic calorimeter embedded in a 0.4-T dipole field. The steel of the magnet yoke will be instrumented with muon identifiers. The strategy to implement the Near Detector is presented in Chapter 5.

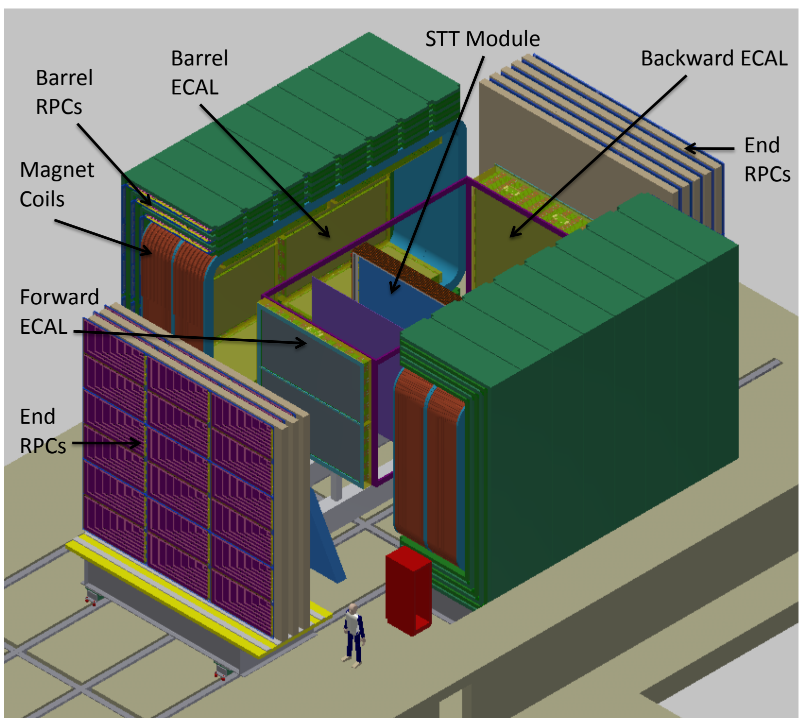

Figure 3.4: A schematic drawing of the fine-grained tracker design

The NND will be complemented by a Beamline Measurement System (BLM) located in the region of the beam absorber at the downstream end of the decay region. The BLM aims to measure the muon fluxes from hadron decay and is intended to monitor the beam profile on a spill-by-spill basis. It will operate for the life of the experiment.

Chapter 4

Organization and Management

4.1 Overview

To accommodate a variety of international funding and organizational constraints, LBNF and DUNE are organized as separate projects. As mentioned in the Introduction, the LBNF Project is responsible for design and construction of the conventional facilities, beamlines, and cryogenic infrastructure needed to support the experiment. The DUNE Project is responsible for the construction and commissioning of the detectors used to pursue the scientific program. LBNF is organized as a DOE/Fermilab project incorporating international partners. DUNE is an international project organized by the DUNE Collaboration with appropriate oversight from stakeholders including the DOE.

4.2 LBNF

4.2.1 Project Structure and Responsibilities

The LBNF Project is charged by Fermilab and DOE to design and construct the conventional and technical facilities needed to support the DUNE Collaboration. LBNF works in close coordination with the DUNE project to ensure that the scientific requirements of the program are satisfied through the mechanisms described in Section 4.4. LBNF also works closely with SURF management to coordinate the design and construction of the underground facilities required for the DUNE far detector.

SDSTA assigns SDSTA engineers and other employees as required to work on specific tasks required for the LBNF project at the SURF site. This is listed in the resource-loaded schedule as contracted work from Fermilab for Far Site CF activities.

LBNF consists of two major L2 subprojects coordinated through a central Project Office located at Fermilab: Far Site Facilities and Near Site Facilities. Each L2 Project incorporates several large L3 subprojects as detailed in the WBS structure presented in Figure 4.1.

The Project team consists of members from Fermilab, CERN, SDSTA, and BNL.

Are we adding a list of acronyms? If not, make sure these are defined in text.

The team, including members of the Project Office as well as the L2 and L3 managers for the individual subprojects, is assembled by the Project Director. Line management for environment, safety and health, and quality assurance flows through the Project Director.

Through their delegated authority and in consultation with major stakeholders, the L2 Project Managers determine which of their lower-tier managers will be Control Account Managers (CAMs) for the Project WBS. L2 and L3 Project Managers are directly responsible for generating and maintaining the cost estimate, schedule, and resource requirements for their subprojects and for meeting the goals of their subprojects within the accepted baseline cost and schedule.

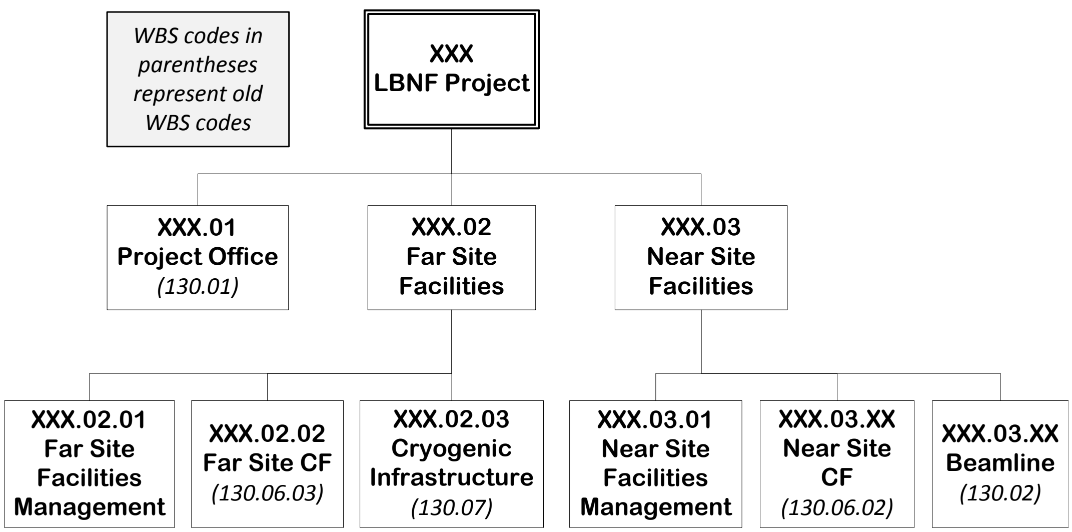

Figure 4.1: LBNF Work Breakdown Structure to WBS Level 3

The design and construction of LBNF is supported by other laboratories and consultants/contractors that provide scientific, engineering, and technical expertise. A full description of LBNF Project Management is contained within the LBNF Project Management Plan

[ref]

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4.2.2 Fermilab

As the host laboratory for the LBNF Project and the Near Site for the Beamline and DUNE Near Detector, Fermilab provides leadership for the LBNF Project. The LBNF Project organization is headed by the LBNF Project Director who is also the Fermilab Deputy Director for LBNF and reports directly to the Fermilab Director. The Project Director also is the head of the Fermilab Divisions containing the resources needed to execute the Far Site Facilities and Near Site Facilities subprojects. Any personnel working more than half-time on these subprojects would typically be expected to become a member of one of these divisions, while other contributors will likely be matrixed in part-time roles from other Fermilab Divisions. The heads of the other Fermilab Divisions work with the L1 and L2 project managers to supply the needed resources on an annual basis. The management structure described above is currently being transitioned into and will not be fully in place until the Fall of 2015.

4.2.3 SDSTA and SURF

LBNF plans to construct facilities at SURF to house the DUNE far detector. SURF is owned by the state of South Dakota and managed by the South Dakota Science and Technology Authority (SDSTA).

define SURF, SDSTA earlier

Current SURF activities include operations necessary for allowing safe access to the 4850L of the mine, which houses the existing and under-development science experiments. The DOE is presently funding SDSTA ongoing operations through Lawrence Berkeley National Laboratory (LBNL) and its SURF Operations Office through FY16; this is expected to change to funding through Fermilab starting in FY17.

The LBNF Far Site Facilities Manager is also an employee of SDSTA and is contracted to Fermilab to provide management and coordination of the Far Site Conventional Facilities (CF) and Cryogenics Infrastructure subprojects. LBNF contracts directly with SDSTA for the design of the required CF at SURF; whereas the actual construction of the CF will be directly contracted from Fermilab. Coordination between SDSTA and the LBNF Project is necessary to ensure efficient operations at SURF. This will be facilitated via an agreement being developed between SDSTA and Fermilab regarding the LBNF Project

[new reference]

that defines responsibilities and methods for working jointly on LBNF Project design and construction. A separate agreement will be written for LBNF Operations.

4.2.4 CERN

The European Organization for Nuclear Research (CERN) will participate in the LBNF Project by providing cryogenic facilities and equipment to support the far detectors as well as some technical components required for the neutrino beamline. As a key partner in the Cryogenics Infrastructure subproject, CERN will provide engineering and technical support for the design and production of specific components and coordinate with others in LBNF on the installation of the identified deliverables. CERN engineers and scientists will participate in the LBNF project as assigned managers for the CERN contributions. Details of the agreements with CERN will be contained in

[name the agreements here]

.

CERN and Fermilab are developing a common cryogenics team to design and produce the Cryogenics Infrastructure subproject deliverables for the far site. CERN provides engineers and other staff as needed to complete their agreed-upon deliverables.

4.2.5 Coordination within LBNF

The LBNF WBS defines the scope of the work. All changes to the WBS must be approved by the LBNF Project Manager prior to implementation. At the time of CD-1-Refresh, the LBNF WBS is in transition. Both the current and the post CD-1-R WBS is shown in Figure 4.1 to demonstrate how the scope will map from one WBS to the other.

LBNF uses internal management boards to coordinate and manage within specific Project areas and across all aspects of the Project. These boards are described here.

Project Management Board: LBNF uses a Project Management Board to provide formal advice to the Project Director on matters of importance to the LBNF Project as a whole. Such matters include (but are not limited to) those that:

- have significant technical, cost, or schedule impact on the Project
- have impacts on more than one L2 subproject
- affect the management systems for the Project
- have impacts on or result from changes to other Projects on which LBNF is dependent
- result from external reviews or reviews called by the Project Director

The Management Board serves as the

- LBNF Change Control Board, as described in the Configuration Management Plan

[ref]

- Risk Management Board, as described in the Fermilab Risk Management Plan

[ref]

Beamline Technical Board: The role of the LBNF Beamline Technical Board (TB) is to provide recommendations and advice to the Beamline Project Manager on important technical decisions that affect the design and construction of the Beamline. The members of the Technical Board must have knowledge of the Project objectives and priorities in order to perform this function. The Beamline Project Manager chairs the Beamline TB. The Beamline Project Engineer is the Scientific Secretary of the Board and co-chairs the Beamline TB as needed.

FSCF Neutrino Cavity Advisory Board: The FSCF Project has engaged three international experts in hard rock underground construction to advise it periodically through the design and construction process regarding excavation at SURF. The board meets at the request of the FSCF-PM, generally on site to discuss specific technical issues. The board produces a report with its findings and conclusions for project information and action.

4.3 DUNE

4.3.1 DUNE Collaboration Structure

The DUNE Collaboration brings together the members of the international science community interested in participating in the DUNE experiment. The Collaboration defines the scientific goals of the experiment and subsequently the requirements on the experimental facilities needed to achieve these goals. The Collaboration also provides the scientific effort required for the design and construction of the DUNE detectors, operation of the experiment, and analysis of the collected data. There are four main elements in the DUNE organizational structure:

- the DUNE Collaboration, composed of the General Assembly of the collaboration and the DUNE Institutional Board (IB)
- DUNE Management, composed of the two co-spokespersons, the Technical Coordinator (TC), and the Resource Coordinator (RC), who along with the IB chair and five other members of the collaboration form the DUNE Executive Committee (EC)
- the DUNE Project Office (PO)
- the DUNE Science Team, including the Physics and Software/Computing coordinators.

The relationships between these entities is illustrated in Figure 4.2.

(for Anne) command to keep figure from floating ...

4.3.2 Responsibilities of the DUNE Leadership

The main responsibilities of the different roles are summarized below:

- **The DUNE General Assembly** is composed of all members of the collaboration, it is consulted on major strategic decisions through open plenary sessions at collaboration meetings and is informed through regular collaboration phone calls;

- **The DUNE Institutional Board** represents the institutes of the collaboration. It is composed of one representative from each of the member institutions and has responsibility for Collaboration governance. The IB has final authority over Collaboration membership issues and defines requirements for inclusion of individuals within the DUNE authorship list. The IB is also responsible for establishing and monitoring the process through which the co-spokespeople are selected to serve as leaders of the collaboration.

- **The DUNE co-spokespersons** are accountable to the collaboration. They are responsible for the day-to-day running of the collaboration and for representing the collaboration to Fermilab, funding agencies, and the broader scientific community.

- **The DUNE Executive Committee (EC)** is chaired by the longest serving co-spokesperson and is the primary decision-making body of the collaboration. Membership of the EC includes the co-spokespeople, DUNE Project Office leaders, IB chair, and five additional Collaboration members (three elected IB representatives and two additional members selected by the co-spokespeople). The EC operates by consensus. In cases where consensus cannot be reached, authority lies with the spokespeople. If the co-spokespeople disagree, the TC will arbitrate.

- **The Technical Coordinator (TC)** reports to the spokespersons and the Fermilab director. The TC acts as the project director and is responsible for the implementation of the scientific and technical strategy of the collaboration through the DUNE project office. The TC is also responsible for the management of the DOE contributions to the DUNE project. The Technical Coordinator prepares and chairs the meetings of the Technical Board of the experiment collaboration.

- **The Technical Board (TB)** discusses and approves the technical planning for all subsystems of the DUNE detector;

- **The Resource Coordinator (RC)** reports to the spokespersons and the Fermilab director. The RC is responsible for coordinating the financial planning and other resources issues of the collaboration. The RC is responsible in particular for the management of the common resources of the Collaboration (common fund). The Resources Coordinator organizes and

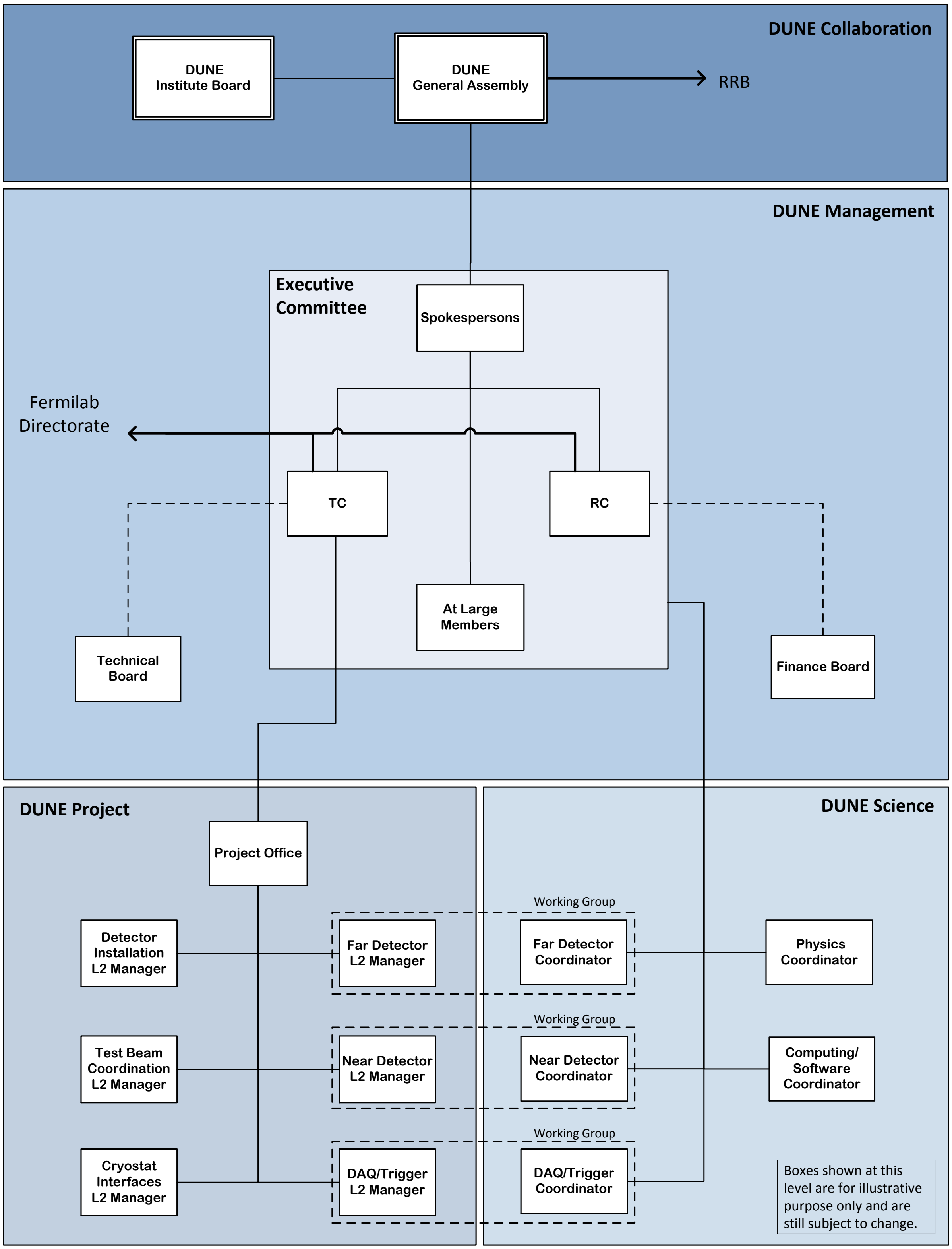

Figure 4.2: DUNE Project and Collaboration Organization

fig:dune

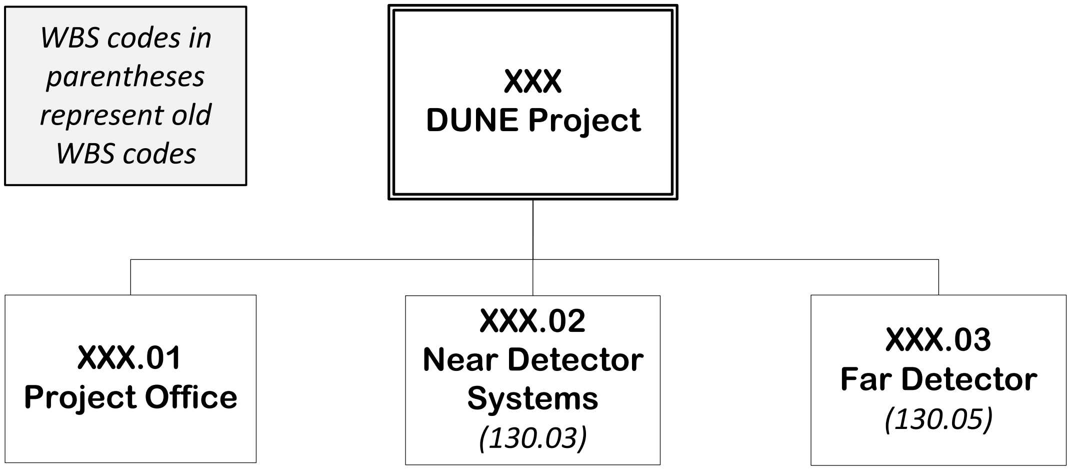

Figure 4.3: DUNE Work Breakdown Structure

chairs the meetings of the Finance Board (internal) of the experiment collaboration. The RC is responsible for the preparation of the Memoranda of Understanding of the Collaboration.

- **The Finance Board (FB)** is responsible for dealing with matters related to the costs and resources of the Collaboration, evaluation of the contributions, relations with the funding agencies and all administrative matters.

- **The DUNE Science Team** is led by the physics coordinator and the software/computing coordinator and is responsible for the management of the DUNE scientific working groups.

- **The DUNE Project Office (PO)** provides the project management for the design, construction, installation, and commissioning of the DUNE near and far detectors. DUNE will be run as an international project matching DOE requirements. This implies maintaining a full cost and schedule for the entire project, from which the DOE-funded portion can be extracted and monitored in a manner that satisfies DOE reporting requirements. The DUNE Project Office will have direct control over DOE project funds and any common fund collected from the U.S. and international stakeholders. International contributions to the DUNE project will be in the form of deliverables as defined in formal Memoranda of Understanding (MOU). These contributions will be tracked through detailed sub-project milestones. The entire Project (including international contributions) will be subject to the DOE critical decision process incorporating a CD-2 approval of its baseline cost and schedule and a CD-3 approval for moving forward with construction. The high-level WBS structure of the Project is illustrated in Figure 4.3.

- **DUNE Technical Working Groups** The organization of the technical working groups of the DUNE collaboration is the responsibility of the L2 managers in the DUNE project.

4.4 LBNF/DUNE Advisory and Coordinating Structures

The LBNF and DUNE projects are overseen by a number of advisory and coordinating bodies as shown in Figure 4.4. The role of the different bodies are described in the following sections.

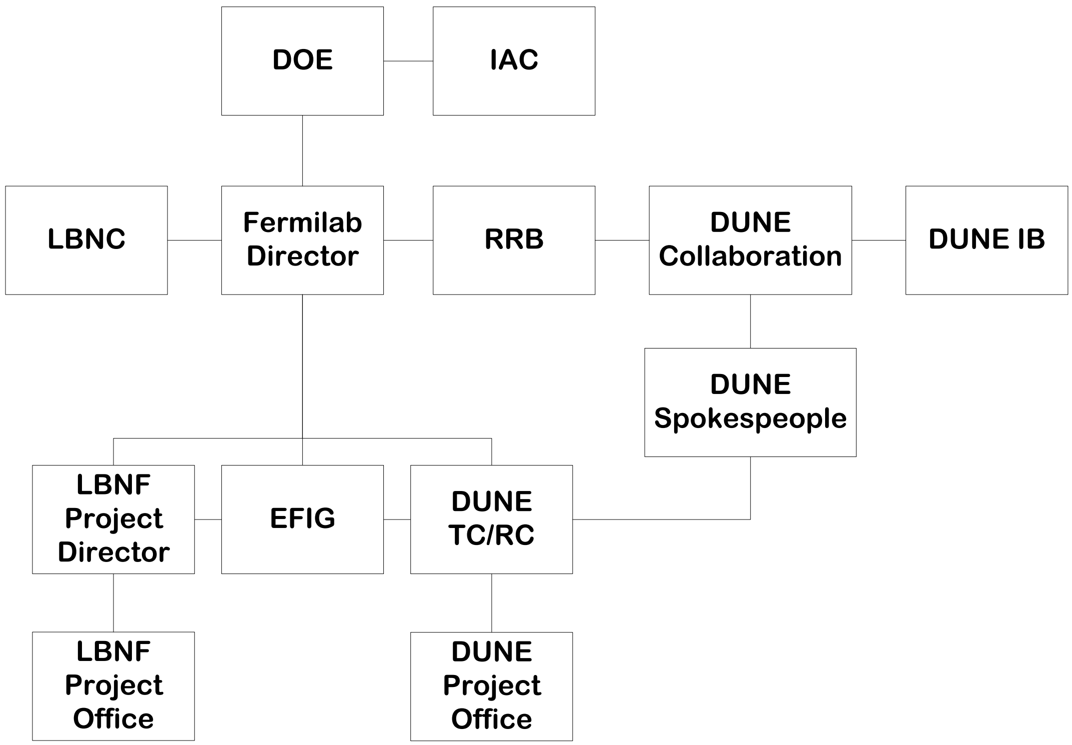

Figure 4.4: LBNF/DUNE Project Structure

4.4.1 International Advisory Committee (IAC)

The International Advisory Committee (IAC) provides primary oversight and coordination of the two projects. This group is made up representatives from each of the funding agencies involved in the program and provides global coordination across the entire enterprise. In particular, this group is responsible for developing a plan that divides the financial responsibilities for constructing the facilities and detectors. This group also has a leading role in developing the bi-lateral and subsidiary agreements between the DOE and other international stakeholders required to advance the program.

4.4.2 Fermilab, the Host Laboratory

As the host laboratory, Fermilab has a direct responsibility for the design, construction, commissioning, and operation of the facilities and infrastructure that support the program. In this capacity, Fermilab reports directly to the DOE through the Fermilab Site Office (FSO). Fermilab also has an important oversight role for the DUNE project itself as well as an important coordination role in ensuring that interface issues between the two projects are completely understood.

4.4.3 LBNC Advisory Committee

The LBNC is an international, external advisory committee tasked with providing peer review for the two projects. This group monitors the projects through regular meetings with the management teams and provides guidance to the Fermilab director in his oversight role. The Fermilab director appoints the head of this committee, who is then responsible for appointing additional committee members.

The LBNC Advisory Committee body needs to be distinguished better from the IAC; e.g., if the IAC is more about funding, is this more about science?

4.4.4 Resource Research Board (RRB)

This body serves as the operational arm of the International Advisory Committee. The Fermilab Director in coordination with the DUNE RC defines its membership, which includes representatives of the funding agencies contributing to the projects. The deputy lab director is the chair of the board and organizes regular meetings to ensure that the needed flow of funding to the projects is maintained. The RRB is charged with defining different national contributions to the projects and the associated Memoranda of Understanding. It is also responsible for understanding in-kind contributions to common projects.

4.4.5 Experiment-Facility Interface Group (EFIG)

The EFIG is the official body tasked with coordinating the LBNF and DUNE projects. The Fermilab director controls the membership of this group, and his deputy serves as its head. Group membership includes members of the Fermilab management such as the Chief Project Officer, members of the LBNF project management team, the DUNE co-spokespeople, as well as the DUNE Technical and Resource Coordinators. The director at his discretion appoints additional members to ensure fulfillment of the group functions, which are to oversee and ensure the required coordination of the LBNF and DUNE projects during the design, construction, and operational phases of the program.

4.4.6 DUNE Collaboration

The collaboration, in consultation with the Fermilab Director, is responsible for forming the international project team responsible for designing and constructing the detectors. The Technical

Coordinator (TC) and Resource Coordinator (RC) serve as the lead managers of this international project team and are selected jointly by the spokespeople and the Fermilab director. Because the international project incorporates contributions from a number of different funding agencies, the international DUNE project is responsible for satisfying individual tracking and reporting requirements associated with each of the different contributions.

Chapter 5

Strategy

strategy

Some dates in this section are being revised as the resource-loaded schedule is matched to DOE funding guidance. Revised dates are expected soon.

Recommendation 12 of the Report of the Particle Physics Project Prioritization Panel (P5) states that for a Long-Baseline Neutrino Oscillation Experiment "The minimum requirements to proceed are the identified capability to reach an exposure of 120kt $\cdot$ MW $\cdot$ year by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime." Based on the resource-loaded schedules for the reference designs of the facility (Volume 3: The Long-Baseline Neutrino Facility for DUNE) and the detectors (Volume 4: The DUNE Detectors at LBNF), the strategy presented here meets these criteria. The P5 recommendations are also in line with the CERN European Strategy for Particle Physics (ESPP) of 2013, which classified the long-baseline neutrino program as one of the four scientific objectives with required international infrastructure.

5.1 Global DUNE-LBNF Strategy

The project strategy presented in this CDR has been developed to meet the requirements set out in the P5 report and takes into account the recommendations of the European ESPP strategy, adopting a model where the U.S. DOE and international funding agencies share costs on the DUNE detectors, and CERN provides in-kind contributions to the supporting infrastructure.

The Long-Baseline Neutrino Facility (LBNF) provides:

- excavation of four underground caverns, each capable of hosting a cryostat with a 10-kt fiducial mass LArTPC, is planned to be completed by 20yy under a single contract

- surface, shaft, and underground infrastructure to support the outfitting of the caverns with four free-standing steel-supported cryostats and the required cryogenic systems. The first two cryostats will be available for filling by 20yy, allowing for a rapid deployment of the first two 10-kt far detector modules. The intention is to install third and fourth cryostats as rapidly as funding will allow.

- the conventional facilities for the near detector systems at Fermilab

- the conventional and technical facilities for a 1.2-MW neutrino beam utilizing the PIP-II upgrade of the Fermilab accelerator complex, operational at the latest by 20yy and upgradable to 2.4 MW with the proposed PIP-III upgrade

The Deep Underground Neutrino Experiment (DUNE) will provide:

- four LArTPCs, each with a fiducial mass of at least 10 kt. The division of the far detector into four equal-mass detectors provides the project flexibility in the installation and funding (DOE vs. non-DOE) in the case of new resources being identified; this division also mitigates risks and allows for an early and graded science return.

- the near detector systems, consisting of a highly-capable neutrino detector and the muon monitoring system necessary to reach the precision requirements needed to fully exploit the statistical power of the very massive far detector coupled to the powerful MW-class neutrino beam

Based on the reference design described below and in Volumes 2, 3 and 4 of the LBNF/DUNE CDR, the resource-loaded schedule will see the first two 10 kt far detector modules operational by 20yy, with first beam shortly afterward. At that time the cavern space for all four 10-kt far detector modules will be available, allowing for an accelerated installation schedule, if sufficient resources for the experiment can be established on an accelerated timescale.

The project strategy described above meets these goals, reaching an exposure of 120kt $\cdot$ MW $\cdot$ year by 2032, and potentially earlier if additional resources are identified. The P5 recommendation of sensitivity to CP violation of 3σ for 75% of δ_{CP} values can be reached with an exposure of 850kt $\cdot$ MW $\cdot$ year with an optimized beam.

5.2 A Strategy for Implementing the DUNE Far Detector

The LBNF project will provide four separate cryostats to be located on the 4850L at the Sanford Underground Research Facility (SURF). Instrumentation of the first cryostat will commence in 20yy. As part of the deployment and risk mitigation strategy, the cryostat for the second detector must be available when the first cryostat is filled. The aim is to install third and fourth cryostats as rapidly thereafter as funding allows.

The DUNE collaboration aims to deploy four 10-kt (fiducial) mass FD modules based on the

Liquid Argon Time Projection Chamber (LArTPC) technology. The viability of the basic LArTPC technology has been proven by the ICARUS experiment. Neutrino interactions in liquid argon produce ionization and scintillation signals. While the basic detection method is the same, DUNE contemplates two options for the readout of the ionization signals: single-phase readout, where the ionization is detected using readout (wire) planes in the liquid argon volume; and the dual-phase approach, where the ionization signals are amplified and detected in gaseous argon above the liquid surface. The dual-phase approach, if demonstrated, would allow for a 3-mm readout pitch, a lower detection energy threshold, and potentially better reconstruction of the events. The DUNE single-phase readout design is being validated in the 35-t prototype detector at Fermilab. A 20-t dual-phase readout prototype is being constructed at CERN and will operate in 2016. An active development program for both technologies is being pursued in the context of the Fermilab Short-Baseline Neutrino (SBN) program and the CERN Neutrino Platform. A flexible approach to the DUNE far detector designs offers the potential to bring additional interest and resources into the experimental collaboration.

5.3 Guiding Principles for the DUNE Far Detector

- The lowest-risk design for the first 10-kt module satisfying the requirements will be adopted, allowing for its installation at SURF to commence in 20yy. Installation of the second 10-kt module should commence before 20yy.

- Recognition that the LArTPC technology will continue to evolve with: (1) the large-scale prototypes at the CERN Neutrino Platform and the experience from the Fermilab SBN program, and (2) the experience gained during the construction and commissioning of the first 10-kt module. It is assumed that all four modules will be similar but not necessarily identical.

- In order to start installation on the timescale of 20yy, the first 10-kt module will be based on the APA/CPA design, which is currently the lowest risk option. There will be a clear and transparent decision process (organized by the DUNE technical board) for the design of the second and subsequent far detector modules, allowing for evolution of the LArTPC technology to be implemented. The decision will be based on physics performance, technical and schedule risks, costs and funding opportunities.

- The DUNE Collaboration will instrument the second cryostat as soon as possible.

- A comprehensive list of synergies between the reference and alternative designs has been identified and summarized in Volume 4: The DUNE Detectors at LBNF. Common solutions for DAQ, electronics, HV feed-throughs, etc., will be pursued and implemented, independent of the details of the TPC design.

5.3.1 Strategy for the First 10-kt Far Detector TPC

The viability of wire-plane LArTPC readout has already been demonstrated by the ICARUS T600 experiment, where data were successfully accumulated over a period of three years. An extrapolation of the observed performance and the implementation of improvements in the design (such as immersed cold electronics) will allow the single-phase approach to meet the LBNF/DUNE far detector requirements. In order to start the FD installation by 20yy, the first 10-kt module will be based on the single-phase design using anode and cathode plane assemblies (APAs and CPAs), described in Chapter 4 of Volume 4: The DUNE Detectors at LBNF. Based on previous experience and the future development path in the Fermilab SBN program and at the CERN Neutrino Platform, this choice represents the lowest-risk option for installation of the first 10-kt FD module by 20yy. For these reasons, the APA/CPA single-phase wire plane LArTPC readout concept is the *reference design* for the far detector. The design is already relatively advanced for the conceptual stage. From this point on, modifications to the reference design will require approval by the DUNE Technical Board. A preliminary design review will take place as early as possible, utilizing the experience from the DUNE 35-t prototype; the design review will define the baseline design that will form the basis of the TDR (CD-2). At that point, the design will be put under a formal change-control process.

A single-phase engineering prototype, comprising six full-sized drift cells of the TDR engineering baseline, will be validated at the CERN neutrino platform in 2018 (pending approval by CERN). This prototype is a central part of the risk-mitigation strategy for the first 10-kt module and is part of the DOE-funded portion of the DUNE project. Based on the performance of this prototype at the CERN Neutrino Platform, a final design review will take place towards the end of 2018 and construction of the readout planes will commence in 2019, to be ready for first installation in 20yy. The design reviews will be organized by the DUNE Technical Coordinator.

In parallel with preparation for construction of the first 10-kt far detector module,

Do we want to use FD and ND or spell them out each time?

the DUNE collaboration recognizes the potential of the dual-phase technology and strongly endorses the already approved development program at the CERN Neutrino Platform (the WA105 experiment), which includes the operation of the 20-t prototype in 2016 and the $6\times6\times6\,\mathrm{m}^3$ demonstrator in 2018. Participation in the WA105 experiment is open to all DUNE collaborators. A concept for the dual-phase implementation of a far detector module is presented as an *alternative design* in Volume 4: The DUNE Detectors at LBNF. This alternative design, if demonstrated, could form the basis of the second or subsequent 10-kt modules, in particular to achieve improved detector performances in a cost-effective way.

5.3.2 DUNE at the CERN Neutrino Platform

WA105 has signed an MoU with the CERN Neutrino Platform to provide a large $\sim 8\times8\times8\,\mathrm{m}^3$ cryostat by October 2016 in the new EHN1 extension, and it is foreseen that a second large cryostat to house the single-phase LArTPC will be provided on a similar timescale. Both will be exposed to charged-particle test beam spanning a range of particle types and energies.

The DUNE collaboration will instrument one of these cryostats with an arrangement of six APAs and six CPAs, in a APA:CPA:APA configuration providing an engineering test of the full-size drift volume. These will be produced at two or more sites with the cost shared between the DOE project and international partners. The CERN prototype thus provides the opportunity for the production sites to validate the manufacturing procedure ahead of large-scale production for the far detector. Three major operational milestones are defined for this single-phase prototype: (1) engineering validation — successful cool-down;(2) operational validation — successful TPC readout with cosmic-ray muons; and (3) physics validation with test-beam data. Reaching milestone 2, scheduled for early 2018, will allow the retirement of a number of technical risks for the construction of the first 10-kt module. The proposal for the DUNE single-phase prototype will be presented to the CERN SPSC in June 2015.

In parallel, the WA105 experiment approved by the CERN Research Board in 2014 and supported by the CERN Neutrino Platform has a funded plan to construct and operate a large-scale demonstrator utilizing the dual-phase readout in the test beam by October 2017. Successful operation and demonstration of long-term stability of the WA105 demonstrator will establish this technological solution as an option for the second or subsequent far detector modules. The DUNE dual-phase design is based on independent $3{\times}3\,\mathrm{m}^2$ charge readout planes (CRP) placed at the gas-liquid interface. Each module provides two perpendicular "collection" views with 3-mm readout pitch. A 10-kt module would be composed of 80 CRPs hanging from the top of the cryostat, decoupled from the field cage and cathode. The WA105 demonstrator will contain four $3{\times}3\mathrm{m}^2$ CRPs of the DUNE type giving the opportunity to validate the manufacturing procedure ahead of large-scale production. WA105 is presently constructing a $3{\times}1\,\mathrm{m}^2$ CRP to be operated in 2016. The same operational milestones (engineering, operational, physics) are defined as for the single-phase prototype.

The DUNE program at the CERN Neutrino Platform will be coordinated by a single L2 manager. Common technical solutions will be adopted wherever possible for the DUNE single-phase engineering prototype and the dual-phase (WA105) demonstrator. The charged-particle test-beam data will provide essential calibration samples for both technologies and will enable a direct comparison of the relative physics capabilities of the single-phase and dual-phase TPC readout.

5.3.3 Strategy for the Second and Subsequent 10-kt Far Detector Modules

For the purposes of cost and schedule, the reference design for the first module is taken as the reference design for the subsequent three modules. However, the experience with the first 10-kt module and the development activities at the CERN Neutrino Platform are likely to lead to the evolution of the TPC technology, both in terms of refinements to single-phase design and the validation of the operation of the dual-phase design. The DUNE technical board will instigate a formal review of the design for the second module in 20yy; the technology choice will be based on risk, cost (including the potential benefits of additional non-DOE funding) and physics performance (as established in the CERN charged-particle test beam). After the decision, the design of the second module will come under formal change control. This process will be repeated for the third and fourth modules in 20yy.

This strategy allows flexibility with respect to international contributions, enabling the DUNE collaboration to adopt evolving approaches for subsequent modules. This approach provides the possibility of attracting interest and resources from a broader community, and space for flexibility to respond to the funding constraints from different sources.

5.4 A Strategy for Implementing the DUNE Near Detector(s)

The LBNF project will provide the facilities for the DUNE near detector systems (muon monitors and near neutrino detector). The primary scientific motivation for the DUNE near detector system is to determine the beam spectrum for the long-baseline neutrino oscillation studies. The near detector, which is exposed to an intense flux of neutrinos, also enables a wealth of fundamental neutrino interaction measurements, which are an important part of the scientific goals of the DUNE collaboration. Within the former LBNE collaboration the neutrino near detector (NND) design was the NOMAD-inspired fine-grained tracker (FGT), which was established through a strong collaboration of U.S. and Indian institutes.

5.4.1 Guiding Principles for the DUNE Near Detector

- The primary design consideration of the DUNE neutrino near detector is the ability to adequately constrain the systematic errors in the DUNE LBL oscillation analysis; this requires the capability to precisely measure exclusive neutrino interactions.
- An additional design consideration for the DUNE NND is the self-contained non-oscillation neutrino physics program.
- It is recognized that a detailed cost-benefit study of potential near detector options has yet to take place and such a study is of high priority to the DUNE project.

  DUNE Project or Collaboration?

5.4.2 The DUNE Near Detector Reference Design

The NOMAD-inspired fine-grained tracker (FGT) concept is the *reference design* for CD-1 review. The cost and resource-loaded schedule for CD-1 review will be based on this design, as will the near site conventional facilities. The Fine-Grained Tracker consists of: central straw-tube tracker (STT) of volume 3.5 m×3.5 m×6.4 m; a lead-scintillator sandwich sampling electromagnetic calorimeter

(ECAL); a large-bore warm dipole magnet, with inner dimensions of $4.5\,\text{m}\times4.5\,\text{m}\times8.0\,\text{m}$, surrounding the STT and ECAL and providing a magnetic field of 0.4 T; and RPC-based muon detectors (MuIDs) located in the steel of the magnet, as well as upstream and downstream of the STT. The reference design is presented in Chapter 7 of Volume 4: The DUNE Detectors at LBNF.

For ten years of operation in the LBNF 1.2-MW beam (5 years neutrinos + 5 years antineutrinos), the near detector will record a sample of more than 100 million neutrino interactions and 50 million antineutrino interactions. These vast samples of neutrino interactions shall provide the necessary strong constraints on the systematic uncertainties for the LBL oscillation physics — the justification is given in Section 6.1.1 of Volume Volume 2: The Physics Program for DUNE at LBNF. The large samples of neutrino interactions will also provide significant physics opportunities, including numerous topics for PhD theses.

5.4.3 DUNE Strategy for the Near Detector

The contribution of Indian institutions to the design and construction of the DUNE FGT neutrino near detector is a vital part of the strategy for the construction of the experiment. The reference design will provide a rich self-contained physics program. From the perspective of an ultimate LBL oscillation program, there may be benefits of augmenting the FGT with, for example, a relatively small LArTPC in front of the FGT that would allow for a direct comparison with the far detector. A second line of study would be to augment the straw-tube tracker with a High-Pressure Gaseous Argon TPC. At this stage, the benefits of such options have not been studied; alternative designs for the NND are not presented in the CDR and will be the subject of detailed studies in the coming months.

5.4.4 DUNE Near Detector Task Force

A full end-to-end study of the impact of the FGT NND design on the LBL oscillation systematics has yet to be performed. Many of the elements of such a study are in development, for example the Monte Carlo simulation of the FGT and the adaptation of the T2K framework for implementing ND measurements as constraints in the propagation of systematic uncertainties to the far detector.

After the CD-1-R review, the DUNE collaboration will initiate a detailed study of the optimization of the NND system. To this end a new task force will be set up with the charge of:

- delivering the simulation of the NND reference design and possible alternatives
- undertaking an end-to-end study to provide a quantitative understanding of the power of the NND designs to constrain the systematic uncertainties on the LBL oscillation measurements
- quantifying the benefits of augmenting the reference design with a LArTPC or a high-pressure gaseous argon TPC

High priority will be placed on this work and the intention is to engage a broad cross section of the collaboration in this process. The task force will be charged to deliver a report by July 2016. Based on the report of this task force and input from the DUNE Technical Board, the DUNE Executive Board will refine the DUNE strategy for the near detector.